Appendix A. Methods of Dose Calculations

S. Ring Peterson

Introduction

Lawrence Livermore National Laboratory calculates doses to the public for radiation protection purposes using the U.S. Environmental Protection Agency's (EPA's) model, CAP88-PC (Parks 1992, 1997), and discusses them in detail in Chapter 13. Emission rates of radionuclides from stacks and diffuse sources are used as input to CAP88-PC. Alternatively, doses may be calculated from concentrations in air, vegetation, water, and wine measured during routine monitoring. Because CAP88-PC is expected to overestimate doses to the public, doses calculated from environmental measurements should be lower, even when assumptions about intake rates are conservative. Calculating dose from measured environmental concentrations will reduce the uncertainty and increase the accuracy of the dose assessment.

Although various radionuclides are released to the environment in small quantities by LLNL activities, tritium is the only radionuclide that can be measured in the local food chain. Furthermore, tritium is the radionuclide primarily responsible for the low dose received by the public. Thus, although some of the equations presented in this chapter can be applied to any radionuclide, only the dose from tritium will be calculated and discussed here.

In this appendix, two different models that may be used to calculate dose from measured environmental concentrations are presented. One model, the Nuclear Regulatory Commission's (NRC) Regulatory Guide 1.109 (U.S. NRC 1977), has been used by LLNL since 1979 (Silver et al. 1980) to calculate ingestion doses from measured environmental concentrations of tritiated water (HTO). Doses have been based on the assumption of maximum annual intake of water, leafy vegetables, milk and meat. Inhalation doses have also been calculated based on measured air concentrations. Equations that derive bulk transfer parameter values used in Chapters 5, 7, and 11 to calculate doses from inhalation and ingestion of water and locally produced foodstuffs based on measured concentrations in the various media are presented here as they have been for twenty-one years. In addition, for comparison, bulk transfer parameter values based on the NRC 1.109 equations with different assumptions are derived. Similarly, bulk transfer parameter values are derived to calculate inhalation dose from predicted air concentrations of tritiated hydrogen gas (HT) and immersion dose from swimming. Using NRC 1.109 with various assumptions, including that of dose from organically bound tritium (OBT), doses based on 2000 environmental measurements are calculated. These doses are compared with those predicted for 2000 by NEWTRIT, the other model used to calculate doses from environmental measurements in this appendix. NEWTRIT has been recently developed and proposed as an improved regulatory model (Peterson and Davis, in press). NEWTRIT accounts for dose contributions from OBT and doses from releases of both HTO and HT.

Overview of CAP88-PC, NRC 1.109 and NEWTRIT

The annual whole-body dose rate from ingestion of a particular food or drink is expressible as a product of three factors, regardless of model. These three factors are (1) the rate at which the food or drink is consumed (e.g., kg/y), (2) the radionuclide concentration in the food or drink (e.g., Bq/kg), and (3) the dose coefficient for the radionuclide (e.g., μSv/Bq). Calculating the dose contribution from inhalation will be similar (e.g., $m^3/y \times Bq/m^3 \times \mu Sv/Bq$). Each of the three models, CAP88-PC, NRC 1.109, and NEWTRIT, approaches this calculation of dose from exposure to environmental tritium in a somewhat different way.

CAP88-PC calculates the air concentration at a particular location using a Gaussian dispersion model. Assuming a default annual absolute humidity of 8 g/m^3, CAP88-PC calculates the concentration of HTO in air moisture. The HTO in vegetables, milk and meat is assumed in equilibrium with the HTO in air moisture. The daily diet is assumed to consist of 1560 g of water obtained from food and 1440 g of drinking water (Moore et al. 1979). The fractions of daily water obtained from food that represent vegetables, milk, and meat are 0.505, 0.310, and 0.185 respectively. For an atmospheric release of HTO, drinking water is assumed to have only 1% the tritium concentration of the air moisture.

Measured concentrations of HTO in air (for inhalation dose), water (for drinking water dose), and vegetation (for dose from food ingestion) can be used in NRC 1.109 to calculate doses from exposure to tritium. The equations, shown in detail in the next section, are not unique to tritium. They may be used to calculate the dose from any radionuclide if the appropriate transfer parameter values are known. Historically at LLNL, concentrations in milk and meat have been calculated based on the assumption that pasture ingested by animals has the same tritium concentration as the median measured concentration of HTO in vegetation. Ingestion dose to man was then calculated based on maximum annual intake rates of leafy vegetables, milk, and meat. This approach, although still used for calculations in Chapter 11 and demonstrated in the equations presented here, ignored the important contribution of tritium in the animal's drinking water to the concentration in the animal product. It also ignored the potential contribution to dose from vegetables other than leafy ones. Furthermore, the assumption of maximum annual intake is highly unrealistic. For comparison with doses based on these assumptions that are reported in Chapters 5, 7, and 11, dose calculations using NRC 1.109 will be presented that are based on an average annual intake of a fairly complete diet. The milk and meat concentrations that make up that diet include the contributions from HTO in both ingested vegetation and drinking water. Doses based on NRC 1.109 concentrations in vegetables, milk, and meat that account for a fraction of intake being due to OBT (based on estimated HTO concentrations of foodstuff) will also be presented.

NEWTRIT calculates doses from releases of HT and HTO based on predicted or measured air concentrations. The default absolute humidity, like that in CAP88-PC, is 8 g/m^3, but a site-specific absolute humidity may be substituted. The model is formulated in terms of the tritium-to-hydrogen ratio in each environmental compartment. However, with each transfer, a small reduction in the ratio is introduced to reflect dilution observed in nature. Drinking water for animals is assumed to have half the concentration of air moisture, because small bodies of water exhibit that level of contamination near an atmospheric source of tritium. Drinking water for people is assumed to have 10% the HTO concentration of air moisture, which is the concentration of tritium expected in a large body of water near an atmospheric source of tritium. NEWTRIT accounts for dose from ingested OBT, as well as HTO. Based on experimental data, NEWTRIT accounts for the conversion of HT to HTO in the soil and the re-emission of HTO to the atmosphere from the soil. Doses calculated from a release of HT include inhalation of HT, inhalation and skin-absorption of HTO, ingestion of HTO from drinking water and foods, and ingestion of OBT from foods. Doses from a unit release of HT are expected to be about 10% those from a unit release of HTO. The diet in NEWTRIT is the same as that in GENII (Napier et al. 1988), and it is assumed that the all the food ingested has been grown at the location at which the air concentrations have been estimated.

Each model recommends different consumption rates (see **Table A-1**). In Appendix E of the NRC Regulatory Guide 1.109, two annual diets are recommended, one for maximum intake and one for average intake. The diet shown for CAP88-PC is based on the assumption that the daily intake of 1560 g of water obtained from food accounts for a complete diet. Values for fresh weight, protein, carbohydrate, and fat fractions, used to derive the annual ingestion rates (kg/y) of vegetables, milk and meat based on water equivalent, come from Ciba-Geigy (1981). Assumptions about the fractions of fruit, grain, root crops, and fruit vegetables that make up "produce" come from NRC Regulatory Guide 1.109. Clearly, based on consumption alone (see **Table A-1)**, doses from these models will be different.

Table A-1. Examples of annual inhalation and ingestion rates

	NRC 1.109 maximum	NRC 1.109 average	CAP88-PC	NEWTRIT
Leafy vegetables/other plant products (kg)	64/520	—[a]/190	—[a]/333	15/276
Milk (L)	310	110	183	230
Meat (kg)	110	95	113	98.5
Drinking water (L)	730	370	526	440
Inhalation (m^3)	8000	8000	8038	8521

a Leafy vegetables are included with the other plant products.

Each of the three models uses different dose coefficients. The dose coefficients used in the calculations of HTO dose from NRC 1.109 were obtained from the committed dose equivalent tables for DOE dose calculations (U.S. DOE 1988). They are similar to those specified in ICRP 72, *Age dependent doses to members of the public from intake of radionuclides* (ICRP 1996), which are used in NEWTRIT. The dose calculation for inhalation of tritiated hydrogen (HT) gas uses a dose coefficient from ICRP 71, (ICRP 1995). A comparison of dose coefficients is shown in **Table A-2**.

Assumptions play such a very important part in predicting dose that assumptions must be clearly elucidated, so that the apparent differences in dose predictions may be understood.

Table A-2. Comparison of dose coefficients for tritium (μSv/Bq)

	DOE	CAP88-PC[a]	ICRP
HTO (inhalation, skin absorption)	1.73×10^{-5}	3.41×10^{-5}	1.8×10^{-5}
HT (inhalation)	3.31×10^{-13}[b]	—[c]	1.8×10^{-9}
HTO (ingestion)	1.73×10^{-5}	2.43×10^{-5}	1.8×10^{-5}
OBT (ingestion)	—[c]	—[c]	4.2×10^{-5}

a Computer code required by the EPA for modeling air emissions of radionuclides

b Units are μSv/Bq × s/m^3 because dose is considered external from air submersion.

c Not taken into account

Dose Calculation Methods

Although the analytical laboratories report concentrations in pCi and the DOE's dose coefficients have units of mrem/pCi, LLNL uses Système Internationale (SI) units of becquerel (Bq) for concentration and millisievert (mSv), microsievert (μSv), or nanosievert (nSv) for dose in compliance with Presidential Executive Order 12770, Metric Usage in Federal Government Programs (July 25, 1991). The conversion factors are as follows:

1 Bq = 27 pCi
1 mSv = 100 mrem; 1 μSv = 0.1 mrem; 1 nSv = 0.1 μrem

All units have been converted to SI units in the following dose calculations.

Note: In some of the following equations, the dimensions associated with a multiplicative factor are not shown explicitly; the dimensions of the dependent variable and measured quantity are shown explicitly.

Dose Calculation Methods for Chapters 5, 7, and 11 Using NRC 1.109

In the following subsections, equations from NRC 1.109 provide guidance to estimate the annual dose from inhalation and from tritium ingested from water (or wine) and food (e.g., leafy vegetables, milk, and meat).

Calculating Annual Dose from Potable Water (Chapter 7)

The effective dose equivalent for tritium in drinking water (D_{water}) in μSv/y is calculated using the following equation:

$$D_{water}\ (\mu Sv/y) = U_w \times DC_{HTO} \times C_w \qquad \text{(A-1)}$$

where

U_w = water consumption rate (L/y)

DC_{HTO} = dose coefficient for HTO (µSv/Bq)

C_w = concentration of tritium measured in drinking water (Bq/L)

The tritium dose from ingestion of potable water, assuming maximum intake of water, is then

$$\mathrm{D}_{water}\ (\mu Sv/y) = 730\ (L/y) \times 1.73 \times 10^{-5}\ (\mu Sv/Bq) \times C_w\ (Bq/L)$$

$$= 1.3 \times 10^{-2} \times C_w\ (Bq/L)$$

In Chapter 7, this equation is used to estimate doses from drinking water. Assuming different quantities are consumed, this equation can also be used to calculate the effective dose equivalent from wine (see Chapter 11).

Calculating Annual Dose from Food Ingestion (Chapter 11)

The effective dose equivalent from ingestion of food (D_{food}) is calculated by summing the contributions from leafy vegetables, meat, and milk to the diet. The concentrations in these foodstuffs are based on measured tritium concentrations in annual grasses or weeds (see Chapter 11). Concentrations in milk and meat are calculated from measured concentrations in vegetation using the equations from NRC Regulatory Guide 1.109.

Leafy Vegetables: For dose calculations, we make the assumption that the leafy vegetables are 100% water; therefore, Bq/L = Bq/kg fresh weight.

$$D_{veg}\ (\mu Sv/y) = U_{veg} \times DC_{HTO} \times C_{veg} \qquad \text{(A-2)}$$

where

U_{veg} = intake rate of leafy vegetables (kg/y)

DC_{HTO} = dose coefficient for HTO (µSv/Bq) (U.S. DOE 1988)

C_{veg} = concentration measured in annual grasses and weeds (Bq/L)

The tritium dose from ingestion of leafy vegetables, assuming maximum intake, is then

$$D_{veg}\ (\mu Sv/y) = 64\ (kg/y) \times 1.73 \times 10^{-5}\ (\mu Sv/Bq) \times C_{veg}\ (Bq/kg)$$

$$= 1.1 \times 10^{-3} \times C_{veg}\ (Bq/L)$$

Meat (Beef): To calculate dose from ingestion of meat, first the concentration of tritium in the meat must be calculated from the measured concentration in vegetation.

$$C_{\text{meat\_veg}} = F_{\text{f}}\,(\text{d/kg}) \times Q_{\text{f}}\,(\text{kg/d}) \times C_{\text{veg}}\,(\text{Bq/kg}) \times \exp(-\lambda_{\text{i}} t_{\text{s}}) \qquad \text{(A-3)}$$

where

F_{f} = average fraction of an animal's daily intake of radionuclide appearing in each kilogram of animal flesh [(Bq/kg) in meat per (Bq/d) ingested by the animal] = 1.2×10^{-2} d/kg

Q_{f} = amount of feed consumed = 50 kg/d

C_{veg} = concentration measured in vegetation (Bq/kg)

λ_{i} = radiological decay constant = $1.5 \times 10^{-4}\ \text{d}^{-1}$

t_{s} = time from slaughter to consumption = 20 d

Therefore

$$C_{\text{meat\_veg}} = 1.2 \times 10^{-2}\,(\text{d/kg}) \times 50\,(\text{kg/d}) \times C_{\text{veg}}\,(\text{Bq/kg}) \times \exp[(-1.5 \times 10^{-4}) \times 20]$$

$$= 0.6 \times C_{\text{veg}}\,(\text{Bq/kg})$$

The dose from ingestion of meat is calculated:

$$D_{\text{meat}}\,(\mu\text{Sv/y}) = U_{\text{meat}} \times C_{\text{meat}} \times DC_{\text{HTO}} \qquad \text{(A-4)}$$

where

U_{meat} = maximum intake rate (kg/y)

C_{meat} = predicted concentration in meat at time of consumption from the contribution of vegetation = $C_{\text{meat\_veg}}$

DC_{HTO} = dose coefficient for HTO (µSv/Bq)

The tritium dose rate from meat consumption is then

$$D_{\text{meat}}\,(\mu\text{Sv/y}) = 110\,(\text{kg/y}) \times [0.6 \times C_{\text{veg}}\,(\text{Bq/kg})] \times 1.73 \times 10^{-5}\,(\mu\text{Sv/Bq})$$

$$= 1.1 \times 10^{-3} \times \text{C}_{\text{veg}}\,(\text{Bq/L})$$

Cow Milk: To calculate dose from ingestion of milk, first the concentration of tritium in the milk must be calculated from the measured tritium concentration in vegetation.

$$C_{milk\_veg} = F_m\ (d/L) \times Q_f\ (kg/d) \times C_{veg}\ (Bq/kg) \times \exp\ (-\lambda_i t_f) \qquad \text{(A-5)}$$

where

F_m = average fraction of an animal's daily intake of radionuclide appearing in each kilogram of milk [(Bq/L) in milk per (Bq/d) ingested by the animal] = 1.0×10^{-2} d/L

Q_f = amount of feed consumed by the milk cow = 50 kg/d

C_{veg} = concentration measured in vegetation (Bq/kg)

λ_i = radiological decay constant = $1.5 \times 10^{-4}\ d^{-1}$

t_f = time from milking to milk consumption = 2 d

Therefore

$$C_{milk\_veg} = 1.0 \times 10^{-2}\ (d/L) \times 50\ (kg/d) \times C_{veg}\ (Bq/kg) \times \exp[(-1.5 \times 10^{-4}) \times 2]$$

$$= 0.5 \times C_{veg}\ (Bq/L)$$

The dose from consumption of milk is calculated:

$$D_{milk}\ (\mu Sv/y) = U_{milk} \times C_{milk} \times DC_{HTO} \qquad \text{(A-6)}$$

where

U_{milk} = maximum intake rate (L/y)

C_{milk} = predicted concentration in milk at time of consumption from the contribution of vegetation = C_{milk_veg}

DC_{HTO} = dose coefficient for HTO (µSv/Bq)

The tritium dose rate from directly consumed milk is then

$$D_{milk}\ (\mu Sv/y) = 310\ (L/y) \times [0.5 \times C_{veg}\ (Bq/kg)] \times 1.73 \times 10^{-5}\ (\mu Sv/Bq)$$

$$= 2.7 \times 10^{-3} \times C_{veg}\ (Bq/L)$$

Total Food Ingestion: The annual dose from food ingestion as calculated in Chapter 11 based on measured HTO in vegetation is then:

$$D_{food}\,(\mu Sv/y) = D_{veg} + D_{meat} + D_{milk} \qquad \text{(A-7)}$$

where

D_{veg} = dose from ingestion of leafy vegetables (μSv/y)

D_{meat} = dose from ingestion of meat (μSv/y)

D_{milk} = dose from ingestion of milk (μSv/y)

Therefore

$$\begin{aligned} D_{food}\,(\mu Sv/y) &= 1.1 \times 10^{-3} \times C_{veg}\,(Bq/L) && \text{(dose from leafy vegetables)} \\ &+ 1.1 \times 10^{-3} \times C_{veg}\,(Bq/L) && \text{(dose from meat)} \\ &+ 2.7 \times 10^{-3} \times C_{veg}\,(Bq/L) && \text{(dose from milk)} \\ &= 4.9 \times 10^{-3} \times C_{veg}\,(Bq/L) \end{aligned}$$

Calculating Annual Inhalation and Skin Absorption Doses of HTO (Chapter 5)

Doses caused by inhalation of radionuclide-contaminated air can be estimated in a way analogous to the preceding treatment of ingestion doses. The starting point is to evaluate the radionuclide concentration in air, χ (Bq/m^3), at the location of interest. Measurements of tritium in air are found in Chapter 5.

The dose from HTO arises from the processes of inhalation and skin absorption. For inhalation/skin absorption dose, the known concentration of tritium in air is multiplied by the inhalation rate of a human to obtain the number of becquerels of tritium inhaled. Dose coefficients provided by the DOE (U.S. DOE 1988) are used to relate the intake of radioactive material into the body to dose commitment. The dose coefficient for inhalation is the same as for ingestion. However, to account for skin absorption, the inhalation factor is multiplied by 1.5. These dose factors provide estimates of the 50-year dose from a one-year intake of radioactivity.

The inhalation/skin absorption dose is expressible as

$$D_{inh/sa}\,(\mu Sv/y) = 1.5 \times U_{air} \times C_{air} \times DC_{HTO\_inh} \qquad \text{(A-8)}$$

where

1.5 = factor that accounts for skin absorption

U_{air} = air intake rate (m^3/y)

C_{air} = HTO concentration measured in air at the receptor (Bq/m^3)

DC_{HTO_inh} = dose coefficient for inhalation (μSv/Bq)

The whole-body inhalation dose rate from HTO is then

$$D_{inh/sa}\,(\mu Sv/y) = 1.5 \times 8000\ m^3/y \times C_{air} \times 1.73 \times 10^{-5}\ \mu Sv/Bq$$

$$= 0.21 \times C_{air}\ (Bq/m^3)$$

Doses in Chapter 5 are calculated as shown here. The breathing rate of 8000 m^3/y was corrected in 1999 from the 8400 m^3/y used in previous years to conform to NRC 1.109.

Guidance to Calculate Annual Ingestion Dose with NRC 1.109 Using Modified Assumptions: Drinking Water for Animals and Annual Average Ingestion Rates for People

The calculations of ingestion dose for Chapter 11 (shown above) do not account for ingestion of tritiated drinking water by animals, and yet drinking water is an important pathway. In 1998, in this appendix, a new approach to calculating the ingestion dose using NRC 1.109 was introduced that included drinking water for animals. In 1999 two further changes were made: (1) the annual ingestion rate for an individual was changed to include produce as well as leafy vegetables and (2) average ingestion rates, rather than maxima, were used (see **Table A-1**).

To calculate concentrations of tritium in meat and milk resulting from ingestion of water, the contribution of drinking water must be calculated using eqs A-3 and A-5 with two substitutions: (1) the daily intake of water (50 L/d for beef cattle and 60 L/d for milk cows) must replace daily intake of pasture and (2) the measured concentration in potable water must replace the measured concentration in vegetation. When dose is calculated using eqs A-4 and A-6, the tritium contributed by drinking water must be added to the tritium contributed by the vegetation to obtain the concentration in meat or milk from both ingestion sources.

To calculate dose from average rather than maximum ingestion rates, the average NRC 1.109 consumption rates from **Table A-1** are substituted into eqs A-1, A-2, A-4, and A-6.

Complete equations that account for these assumptions may be found in Larson et al. (2000). Bulk transfer factor parameter values based on these assumptions have been calculated using eqs A-2, A-3, A-4, A-5, and A-6. They are summarized and compared in **Table A-3** with the values used for the calculations in Chapters 5, 7 and 11.

Table A-3. Comparison of the two sets of bulk transfer factors based on different assumptions to calculate doses using NRC 1.109

Doses	Assumptions for SAER	Alternate assumptions: tritium in milk and meat comes from pasture and drinking water; average annual diet	
$D_{inh/sa}$	Chapter 5 Inhalation and skin absorption: 0.21 x C_{air} (Bq/m^3)	Inhalation and skin absorption: 0.21 x C_{air} (Bq/m^3)	
D_{water}	Chapter 7 Drinking water: 1.3 x 10^{-2} x C_w	Drinking water: 6.4 x 10^{-3} x C_w	
	Chapter 11 Calculations – food ingestion:	Calculations assuming drinking water for animals and average annual intake for people – food ingestion:	
	Factor x C_{veg} (Bq/kg)	Factor x C_{veg} (Bq/kg)	Factor x C_w (Bq/L)
D_{veg}	1.1 x 10^{-3}	3.7 x 10^{-3}	NA
D_{meat}	1.1 x 10^{-3}	9.9 x 10^{-4}	9.9 x 10^{-4}
D_{milk}	2.7 x 10^{-3}	9.5 x 10^{-4}	1.1 x 10^{-3}

Method to calculate dose from ingestion of OBT

Models that account only for dose from HTO have come under attack in recent years. As shown in **Table A-2**, the dose coefficient for OBT is 2.3 times greater than that of HTO. When it is assumed (as in CAP88-PC and NRC 1.109) that all ingested tritium is HTO, there is a possibility, depending on other assumptions in the models, that dose may be under-estimated. It is easy enough to calculate the probable contribution of OBT to dose, even from a model that only calculates concentrations of HTO and dose from HTO.

At LLNL, the HTO concentration of the plant water is measured in Bq/L. The concentration of tritium in fresh weight plant is the sum of the tritium in the water fraction (HTO) plus the tritium in the dry matter fraction (OBT):

$$\text{Bq/kg fresh weight plant} = (\text{Bq/ L (measured HTO)} \times F_{fw}) + (\text{Bq/ L (measured HTO)} \times F_{dm} \times W_{eq}) \qquad \text{(A-9)}$$

where

F_{fw} = water fraction of the plant (L/kg)

F_{dm} = dry matter fraction of the plant (kg/kg)

W_{eq} = water equivalent factor (L/kg) = amount of water generated through the combustion of the dry material in the sample = [(percent protein × 0.07) + (percent fat × 0.12) + (percent carbohydrate × 0.062)]/ 100 × (1/fraction of mass of water that is hydrogen)

where

0.07 = fraction of hydrogen in proteins

0.12 = fraction of hydrogen in fats

0.062 = fraction of hydrogen in carbohydrates

2/18 = fraction of mass of water that is hydrogen

Values of water fractions and fractions of protein, fat, carbohydrate, and ash for a wide variety of foodstuffs can be found in Ciba-Geigy Ltd. (1981). The W_{eq} varies with the type of food and can be calculated from these data. A median value of W_{eq} for a normal array of foodstuffs is about 0.6 L/kg.

Similarly, concentrations of HTO and OBT per kilogram milk or meat can be estimated based on the total concentrations of milk and meat calculated using eqs A-3 and A-5 and accounting for the contribution of drinking water.

Examples of concentrations of various foodstuffs based on the 2000 median tritium concentrations in plant water (6.2 Bq/L) and rain water (3.0 Bq/L) at VIS (**Table A-4**) are shown below. These equations follow the format of eq A-9, where the total concentration of tritium per kilogram edible food is the sum of the HTO and OBT contributions, respectively.

Lettuce $(6.2 \times 0.948) + (6.2 \times 0.052 \times 0.602) = 5.88 + 0.19 = 6.07$ Bq/kg fresh weight

Potato $(6.2 \times 0.798) + (6.2 \times 0.202 \times 0.568) = 4.95 + 0.71 = 5.66$ Bq/kg fresh weight

Whole milk $(4.9 \times 0.885) + (4.9 \times 0.115 \times 0.746) = 4.34 + 0.42 = 4.76$ Bq/kg fresh weight

Lean sirloin $(4.6 \times 0.718) + (4.6 \times 0.282 \times 0.724) = 3.30 + 0.94 = 4.24$ Bq/kg fresh weight

To calculate dose that accounts for OBT, the concentration of HTO or OBT in each foodstuff must be multiplied by the appropriate dose coefficient (**Table A-2**) and by the quantity consumed. The total food ingestion dose is then the sum of the HTO and OBT dose contributions.

Method to calculate dose from inhalation of HT

In the recent past, HT doses were treated as immersion doses (Eckermann and Ryman 1993), because HT has a low-energy beta particle and behaves similarly to ^{41}Ar. However, the dose from HT is dominated by the small fraction that is metabolized. HT is therefore treated as a soluble gas (ICRP 1994), and an inhalation dose is calculated.

For tritium gas (HT), an inhalation dose is expressible as

$$D_{inh\_HT}\ (\mu Sv/y) = C_{air\_HT} \times U_{air} \times DC_{HT} \qquad \text{(A-10)}$$

where

C_{air_HT} = concentration of HT in air at location X; estimated by dispersion modeling (Bq / m^3)

U_{air} = air intake rate (m^3 / y)

DC_{HT} = effective dose per unit intake (µSv / Bq)

Therefore

$$D_{inh\_HT}\ (\mu Sv/y) = C_{air\_HT}\ (Bq/m^3) \times 8000\ m^3/y \times 1.8 \times 10^{-9}\ \mu Sv/Bq$$

The tritium dose rate from inhalation of HT is then (based on predicted HT in air):

$$D_{inh\_HT}\ (\mu Sv/y) = 1.44 \times 10^{-5} \times C_{air\_HT}\ (Bq/m^3)$$

Method to calculate dose from swimming

Immersion in water is another pathway to dose from tritium because tritium can be absorbed through the skin. The intake of water by skin diffusion is 0.4 mL / min (Osborne 1968). A high estimate of time spent swimming in the LLNL would be 250 hours a year. The amount of water absorbed through the skin in this period would be 6 L.

Dose from immersion in water can be expressed as:

$$D_{imm\_HTO}\ (\mu Sv/y) = C_{pool}\ (Bq/L) \times U_{pool}\ (L/y) \times DC_{HTO}\ (\mu Sv/Bq) \qquad \text{(A-11)}$$

where

C_{pool} = median annual concentration of HTO in the LLNL swimming pool (Bq / L)

U_{pool} = intake rate of water through the skin (L / y)

DC_{HTO} = effective dose per unit intake HTO (µSv / Bq)

The whole-body skin absorption dose from swimming is:

$$D_{imm\_HTO}\ (\mu Sv/y) = C_{pool} \times 6\ L/y\ \times 1.8 \times 10^{-5}\ \mu Sv/Bq$$

$$= 1.1 \times 10^{-4}\ C_{pool}\ (Bq/L)$$

Dose Predictions

Regulatory Dose Predictions

Observed and Predicted Input to Models

Concentrations of tritium in air (Chapter 5) are monitored at 11 on-site locations, including the Visitor's Center (VIS), which is a convenient location for comparing doses from different modeling approaches, because measurements of tritium in vegetation and rainfall are also taken at VIS. Furthermore, VIS is close to the location of the site-wide maximally exposed individual. Median concentrations measured in air, vegetation (Chapter 11) and rainwater (Chapter 7) for VIS are shown in Table A-4 along with predicted air concentrations at VIS for releases from the Tritium Facility using CAP88-PC. If the contribution of all LLNL sources of tritium had been estimated at VIS, the predicted concentrations of tritium in air would be higher. The concentration of tritium in wine (Chapter 11) and the LLNL swimming pool (Chapter 7) are also shown in Table A-4.

Table A-4. Observed tritium concentrations in various environmental media at VIS and in the vicinity of Livermore, and concentrations of HTO and HT in air at VIS predicted by CAP88-PC from releases from the Tritium Facility. All data are for 2000.

	Median Observed HTO Concentrations	Predicted Tritium Concentrations
Air concentration (Bq/m^3)		
HTO	0.047	0.059
HT		0.0070
Vegetation (Bq/L)	6.2	n/a
Rain (Bq/L)	3.0	n/a
Livermore Valley Wine (Bq/L)	2.3	n/a
LLNL Swimming Pool (Bq/L)	2.8	n/a

n/a = not applicable

CAP88-PC doses are calculated based on measured source terms. Doses using NEWTRIT can be estimated using either the observed or predicted air concentrations at VIS. Measured concentrations in vegetation, air, and rainfall at VIS can be used as input to NRC 1.109 to calculate doses. The assumption for all calculations is that the exposed person never leaves the Visitor's Center and is entirely self-sufficient in that all vegetables (including grain) ingested are grown at the Visitor's Center. Furthermore, all animals used for food live there too and consume pasture grown there. Drinking water for both animals and people (in NRC 1.109) is rainwater at the median concentration for the entire year. The assumption that drinking water has the concentration of rain water is extremely conservative and will result in a very high estimate of dose compared with the true probable dose in the Livermore Valley, because no drinking water supplies were above the detection limit for 2000 (Table 7-13). The use of different models and different assumptions will result in very different dose predictions (Tables A-5 and A-6). Because the protection of the public is paramount, it should be shown by more than one model and more than one set of assumptions that the dose to the public is acceptably low.

Comparison of Model Predictions for inhalation and ingestion of HTO: CAP88-PC and NRC 1.109

Results in Table A-5 compare doses predicted by CAP88-PC and the NRC 1.109 model with two different sets of assumptions. Results for NRC 1.109 in the middle column of Table A-5 were calculated using the historical assumptions that have been used in the SAER for dose calculations in the appropriate chapters (i.e., no drinking water for animals and maximum annual ingestion rates of leafy vegetables, milk and meat). Numbers for NRC 1.109 in the right-hand column were calculated based on the assumption of drinking water for animals and an annual average diet. All results are based on the assumption that ingested tritium is only HTO.

The CAP88-PC predictions are all higher than either set of NRC results except for drinking water. The default assumption in CAP88-PC is that drinking water is only 1% as contaminated as air moisture; in NRC 1.109, the assumption has been made that the individual is drinking water with a concentration of 3.0 Bq/L (equal to rain water). Thus, for 2000, the dose from drinking water in NRC 1.109 can be as much as nearly 50% of the total dose, depending upon other assumptions, while in CAP88-PC, the drinking water contribution is less than 1% of the total dose. This illustrates the importance of tritium concentrations in drinking water to total dose.

Table A-5. Comparison of hypothetical annual doses from only HTO at the Visitor's Center

Dose (nSv/y)	CAP88-PC[a] (from predicted air concentrations)	NRC 1.109 (from observed concentrations)—SAER assumptions	NRC 1.109 (from observed concentrations)—new assumptions
Inhalation and skin absorption	16.	9.8	9.8
Vegetables	52.	6.8	20.
Milk	[32.]	17.	9.2
Meat	19.	6.8	9.1
Drinking water	0.95	39.	19.
Total ingestion dose (food and water)	72. [104.]	70.	58.
Total dose from HTO	88. [120.]	79.	67.

a Numbers in brackets (e.g., dose from milk) are not calculated for reported LLNL doses. See *LLNL NESHAPs 1999 Annual Report* (Gallegos et al. 2000), *Guidance for Radiological Dose Assessment* (Harrach 1999), and Chapter 13.

Comparison of Model Predictions for HTO inhalation and ingestion and OBT ingestion: NRC 1.109 and NEWTRIT

Using the assumptions of the NRC 1.109 model (animals drink rainwater and the annual diet is average) and estimated concentrations of HTO and OBT in Bq / kg fresh weight of food, doses for total tritium (HTO and OBT) can be calculated for NRC 1.109 (Table A-6). The contribution of OBT increases the doses over those shown in Table A-5 by 35%, 20% and 43% for vegetables (including grain), milk and meat respectively. In Table A-6, doses from NRC 1.109 that account for OBT are compared with doses calculated from NEWTRIT. Differences are due to different assumptions about diets (see Table A-1) and the fact that NEWTRIT's concentrations in vegetables, milk and meat are lower than those of NRC 1.109. The drinking water tritium contribution to milk and meat is about the same in both models. The contribution of drinking water to human dose in NRC 1.109 is much higher than in NEWTRIT with its default assumption that the concentration of the individual's drinking water is just 10% of the concentration of air moisture. 10% of the median air moisture concentration measured at VIS is 0.59 Bq / L, which is about a factor of 5 lower than the concentration of rainwater. This concentration is also non-detectable using scintillation counting. This estimate is nevertheless conservative, since drinking water in the Livermore Valley does not come from surface water, and it is higher than the prediction of CAP88-PC (see Table A-5).

Table A-6. Comparison of hypothetical annual doses from HTO and OBT at the Visitor's Center

Dose (nSv/y)	NRC 1.109 (from observed air and vegetation concentrations)	NEWTRIT[(a)] for released HTO (from observed air concentrations)	NEWTRIT[(a)] for released HTO (from predicted air concentrations)	NEWTRIT[(a)] for released HT (from predicted air concentrations)
Inhalation	9.8	11.	12.	0.045
Vegetables[(b)]	27.	28.	31.	0.48
Milk	11.	18.	19.	0.23
Meat	13.	8.9.	10.	0.11
Drinking water	19.	4.7	5.1	0.10
Total ingestion (food and water)	70.	60.	65.	0.92
Total dose from HTO and OBT	80.	71.	77.	0.97

a The total tritium dose predicted by NEWTRIT for HT and HTO released from the Tritium Facility will be the sum of the NEWTRIT results for predicted air concentrations of HT and HTO or the sum of the HT results for predicted air concentrations plus the HTO results based on observed air concentrations.

b Includes leafy vegetables, fruit, fruit vegetables, root vegetables and grain

Also shown in **Table A-6** is the estimated dose from the release of HT from the Tritium Facility. A tiny contribution to total dose from inhalation (1.3×10^{-8} nSv/y, not shown explicitly) arises from air concentrations of tritiated hydrogen (HT) gas, based on an air concentration of 0.007 Bq/m^3 estimated by the dispersion model in CAP88-PC. The inhalation dose shown from the release of HT is due to conversion of HT to HTO in the soil and the re-emission of HTO to air. Re-emitted HTO is incorporated into plants. For 2000, the release rate of HT was small relative compared with the release of HTO from the Tritium Facility. As a result, the dose from HT is only about 1% that of the dose from the released HTO. The measured HTO concentrations in air and vegetation account for the dose from any HT that has been converted to HTO in the environment.

The assumptions behind the models in **Tables A-5** and **A-6** are all designed to predict highly conservative doses for regulatory purposes that will not be exceeded by any member of the public. Even the lowest dose from **Tables A-5** and **A-6** (67 nSv/y for NRC 1.109, assumptions of animal drinking water and average diet) is less than a factor of two below the highest dose, which was calculated with CAP88-PC.

Realistic Dose Estimates

NEWTRIT is the model best suited for a realistic dose assessment because it accounts for doses from releases of HT and HTO separately and determines the contribution of OBT to dose. Furthermore, its default parameter values may be altered to account for site-specific data. For example, in this calculation, the average absolute humidity for 2000 at LLNL (7.6 g/m^3) was used instead of the default (8 g/m^3). If it were possible for a person to live at the Visitor's Center, it would still be highly unlikely that they would spend all their time there, or that all their food would be homegrown. This person also might drink local wine and swim in the LLNL swimming pool; these doses can be calculated with the equations presented in this appendix. Realistic, yet still conservative, doses are shown in **Table A-7**.

Table A-7. Realistic, yet conservative, assumptions and consequent doses for the tritium exposure of an individual living at Visitor's Center in 2000 based on observed HTO in air concentrations and predicted HT in air concentrations

Source of dose	Annual dose (nSv)	Assumption
Inhalation	7.3	Breathes air at VIS 16 hours a day, all year
Ingesting food, including OBT	13.0	Raises and eats 50% homegrown leafy vegetables, fruit vegetables, fruits and root crops, no homegrown milk and 20% homegrown meat (chickens and eggs). Assume the feed for the chickens is 50% homegrown; chickens drink water from puddles at 50% air moisture.
Drinking water	0.50	Drinks well water at 1% the concentration of air moisture.
Drinking wine	2.1	Drinks one bottle of Livermore Valley wine each week
Immersion	0.12	Swims in the LLNL pool 100 hours per year

The total annual "realistic" dose from **Table A-7** is therefore 23 nSv/y, a factor of about 5.2 below the maximum dose predicted by CAP88-PC, and a factor of 3.1 below the dose predicted by NEWTRIT, neither of which accounts for wine or swimming.

All calculated doses presented here are about 1% or less of the EPA's radiation dose limit to the member of the public from an atmospheric release (100 μSv/y). CAP88-PC's dose, by far the highest, is just 1.2% of an annual effective dose equivalent of 10 μSv, which corresponds to the National Council on Radiation Protection and Measurements' (1987a) concept of Negligible Individual Risk Level. Thus, even though artificially high, this dose is still small.